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The aim of this paper is to introduce *Virtual Equivalence*, a method to merge real circuits and virtual circuits. Also it is a new method to implement the *Hyper-Bond* (Bruns, 2001) for voltage and current flow. The electric power (current \times voltage) interactions, at which the real electric components can be bi-directionally connected with the virtual electric components, using only one interface port between the real and virtual environment, are presented. With detailed implementations, it will be shown that this method can be applied in various mixed reality models with electric circuits, from learning environments of physics laboratory at school to simulation systems used in industry.

1. Introduction

Most computer interfaces use one-way links between the computer and the real environment to process and display input signals from the real environment, or transmit feedback signals from the computer to the real environment, and it is a one-way signal flow at very low power (current \times voltage). However, in many cases of real electric circuit, the power is of bi-directional nature. To implement a true power interaction, between the virtual component in the computer and the real component in real environment, the same physical law as in the real electric circuit must be applied, and it is inappropriate to use only the one-way link.

The *Hyper-Bond* (Bruns, 2003), bi-directional link between the virtual and the real model, being able to sense and generate various relevant physical continuous *effort* and *flow* phenomena via universal connections, was already introduced and it is supported by *Bond Graphs* (Paynter, 1961; Karnopp, 1995). Bond-Graph theory considers a continuity of energy (Effort \times Flow) flow in abstract networks. Effort can be electric voltage, air pressure, force, momentum, temperature, etc. Flow can be electric currency, air volume flow, velocity, heat-flow etc. For example, in Fig.1, the right is a bond graph of the left electric circuit. Fig. 2 is the implementation of the Hyper-Bonds for electrics (voltage and current) and pneumatics (pressure and volume-flow), together with its abstract bond graph representation. In order to provide arbitrary boundary conditions, it is necessary to have a mechanism to switch between source and sink and to generate one phenomenon and sense the other (Bruns, 2001).

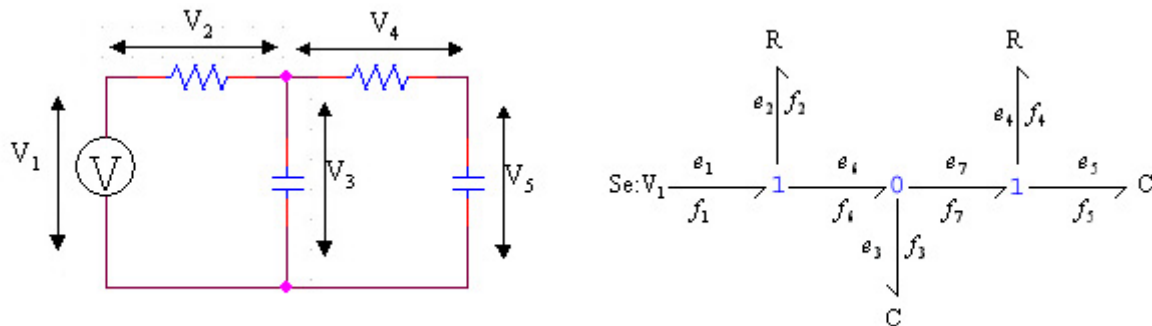


Figure 1. Standard electrical symbols (left) and Bond graph symbols (right)

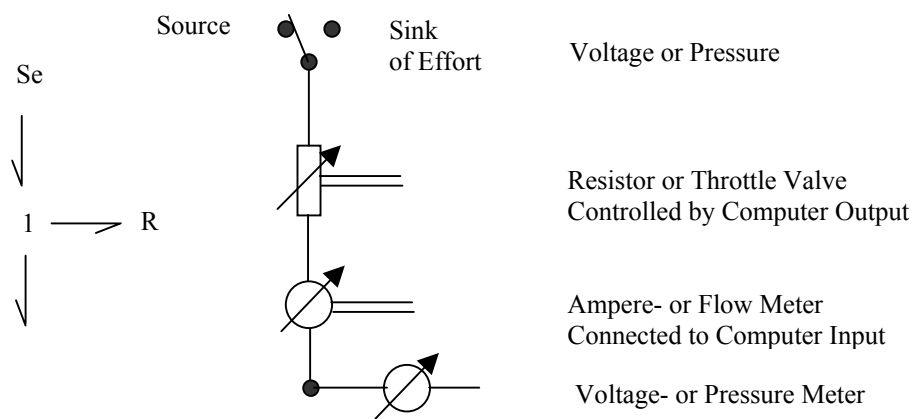


Figure. 2: Hyper-Bond for Voltage/Current- or Pressure/Volume-Flow

Some applications to which the *Hyper-Bond* concept applies have been developed, e.g. mixed reality environments for electro-pneumatic¹ (Fig. 3) and force feedback (Fig. 4), (Bruns, 2003 and Yoo & Bruns, 2004).

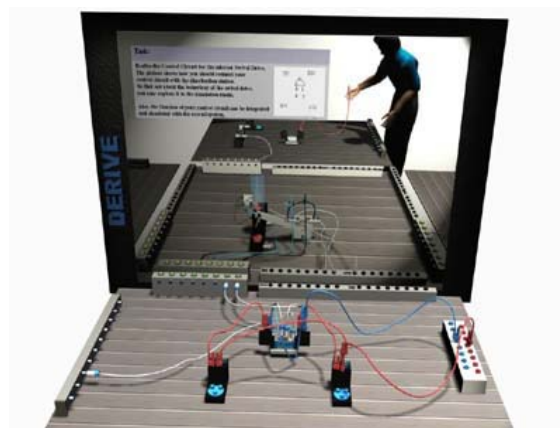


Figure. 3. DERIVE Learning Environment

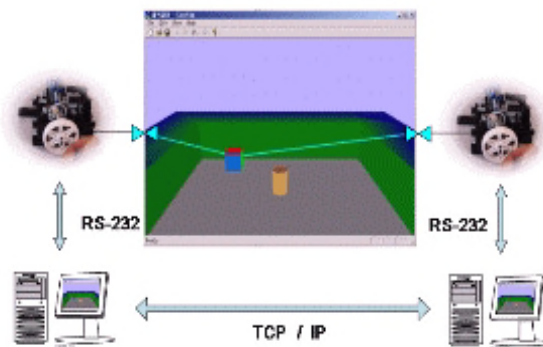


Figure. 4. Distributed Mixed Reality Model

¹ EU-IST Project DERIVE (Distributed Real and Virtual Learning Environment for Mechatronics and Tele-Service)

Virtual equivalence is a new method to implement the Hyper-Bonds for voltage and current flow. In order to bi-directionally connect a virtual circuit with a real circuit, a virtual circuit in the virtual environment is replaced by an equivalent circuit led by the *Thevenin's and Norton's Theorems* (Thevenin, 1883 and Norton, 1926) and physically implemented and connected with the real circuit in the real environment. For realtime Hyper-Bond applications, this method is very effective because it can achieve true power interactions without switching between sink and source. In the next section, its principle and implementations will be introduced.

2. Thevenin's and Norton's Theorems

In order to analyze an electric network, the *Thevenin's and Norton's theorems* are often used and well-known in the circuit analysis field. These are extremely useful circuit analysis theorems which can be used to replace the entire network, exclusive of the load, by an equivalent circuit that contains only an independent voltage source in series with a resistor in such a way that the current-voltage relationship at the load is unchanged. Assuming that Fig.5 is a complex network split into two parts, from which the circuit A must be linear and the circuit B may be linear or nonlinear, the fact that the left of Fig. 6 is equivalent at terminals A-B to circuit A in Fig. 5 is a statement of *Thevenin's theorem*, and the fact that the right of Fig. 6 is equivalent at terminals A-B to circuit A in Fig. 5 is a statement of *Norton's theorem*. Both theorems are complementarily used to analyze an electric network.

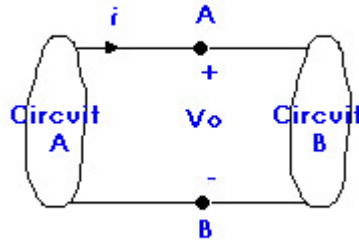


Figure 5. A complex network split into two parts.

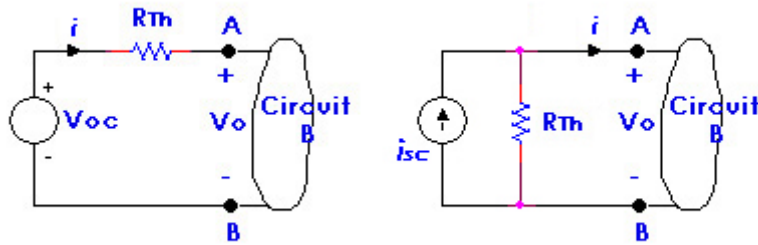


Figure 6. Thevenin and Norton equivalent circuits.

In Fig. 6, R_{th} is the equivalent resistance looking back into circuit A from terminals A-B with all independent sources made zero in circuit A, V_{oc} is the open-circuit voltage of the condition when i is zero, and i_{sc} is the short-circuit current due to all sources in circuit A with V_o replaced by a short circuit. The equations are as follows,

$$V_o = V_{oc} - R_{Th} \cdot i \quad (1.1)$$

$$i = i_{sc} - \frac{V_o}{R_{Th}} \quad (1.2)$$

In Fig. 7, an example of the Thevenin and Norton equivalent theorem is shown for a resistor network where resistors and independent sources exist. Fig. 7a shows a complex circuit; its equivalent circuit is represented in Fig. 7d. From Eq. (1.1) and the condition $i = 0$ (Fig. 7b), it follows $V_{oc} = V_o$. Thus, V_{oc} is calculated from equations (1.3).

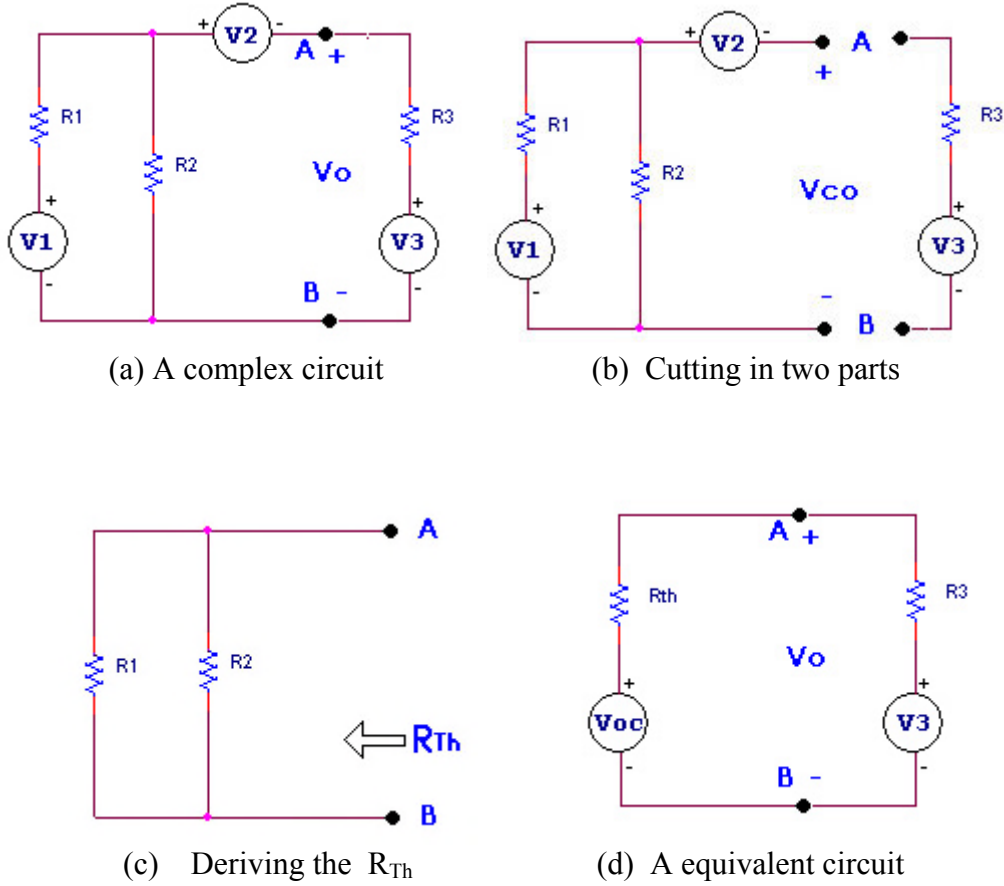


Figure 7. An example of the Thevenin and Norton equivalent theorems

R_{Th} is derived from Fig. 7c. Thus, the equations are as follows,

$$V_{oc} = \frac{R_2}{R_1 + R_2} \cdot V_1 - V_2 \quad (1.3)$$

$$R_{Th} = \frac{R_1 \cdot R_2}{R_1 + R_2} \quad (1.4)$$

The Thevenin and Norton equivalent theorems can also be used to analyze *RLC* (resistors, inductors and capacitors) circuits. However, because the impedance is associated with the frequency, this theorem must be applied with the condition that all independent sources are of sinusoidal voltage form of same frequency, while magnitude and phase can be different. In Fig. 8, another example of the Thevenin and Norton equivalent theorem is shown, where the *RLC* and the independent sources have the same frequency. It can be analyzed with the same process as the previous example. Fig. 8a is a complex *RLC* circuit; its equivalent circuit is Fig. 8d. From Fig. 8b and Fig. 8c, Z_{Th} the equivalent impedance and V_{oc} the open-circuit voltage can be derived; V_{oc} and Z_{Th} are calculated from equations (1.5) and (1.6).

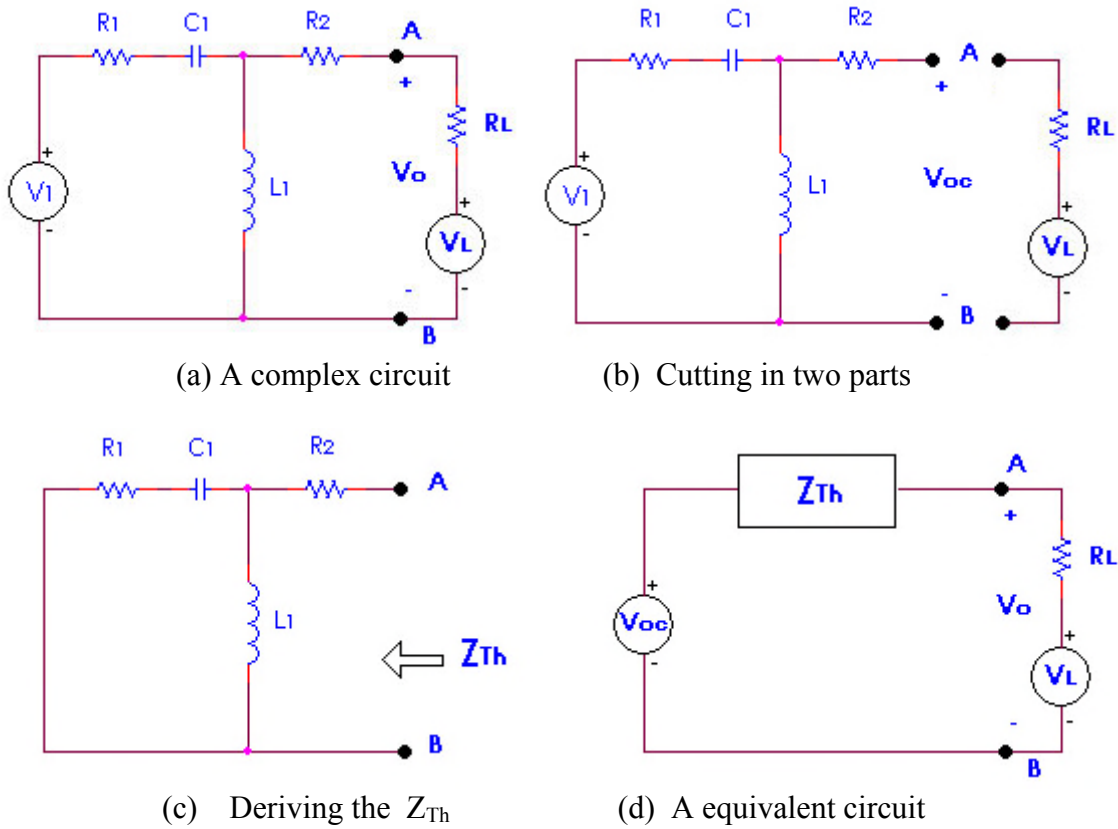


Figure 8. Another example of the Thevenin and Norton equivalent theorem with RLC

$$V_{oc} = \frac{j\omega L_1}{R_1 + j(\omega L_1 - \frac{1}{\omega C_1})} \cdot V_1 \quad (1.5)$$

$$Z_{Th} = \frac{j\omega L_1 \cdot (R_1 - j\frac{1}{\omega C_1})}{R_1 + j(\omega L_1 - \frac{1}{\omega C_1})} + R_2 \quad (1.6)$$

3. Virtual Equivalence

Virtual Equivalence is to replace the arbitrary virtual circuit in virtual environments by an implementation circuit, connected with a real circuit in the real environment, of the virtual equivalence. In the circuit of Fig. 7d, it is possible to use a digital potentiometer, which can be controlled by the computer, to implement the equivalent resistance, R_{Th} . Therefore, the arbitrary virtual circuit can be replaced by a digital potentiometer and a D/A output port which output the signal (V_{oc}) calculated by the computer. It is not necessary to switch between source and sink for the boundary conditions of the real and virtual circuit (Fig. 9).

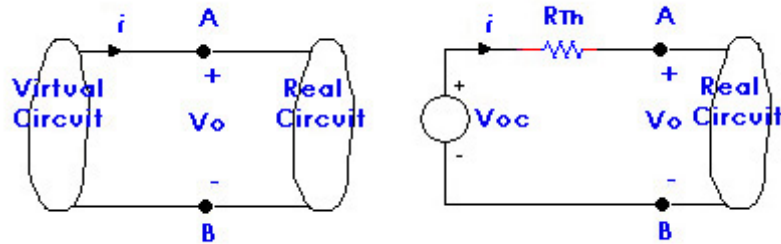


Figure 9. Convert the virtual circuit to a virtual equivalent circuit

Some microelectronic circuits may be used to implement the equivalent resistance or capacitance. The AD8403 of ANALOG DEVICES (Fig.10) provides four channels of each controlling a variable resistor with a resolution of 8 bits. The devices perform the same electronic adjustment function as a potentiometer or variable resistor.

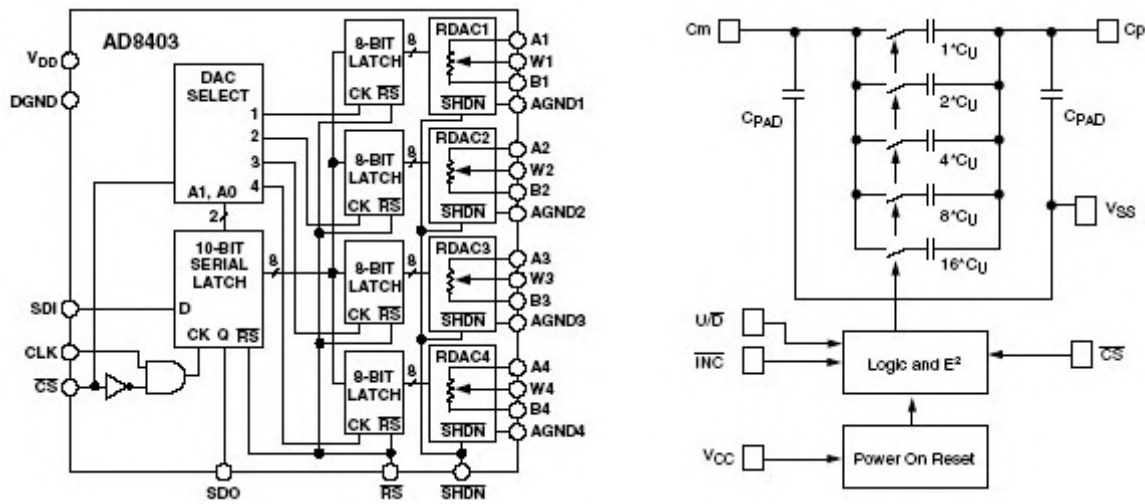


Figure 10. Functional block diagram of the Digital Potentiometer (AD8403, left) and the Programmable Capacitor (X90100, right)

The Xicor X90100 (the right of Fig. 10) is a non-volatile electronically programmable capacitor. With the Thevenin and Norton equivalent theorems, although the *Virtual Equivalence* method can be theoretically applied to any RLC circuits, its implementation is not trivial, because it is a very difficult task to control the inductance with a computer.

4. Implementation of 2-Port Virtual Equivalence with Digital Potentiometer

A simple method to actually implement *Virtual Equivalence* of Fig. 11 is to transmit a V_{oc} signal, from PC to a V_{oc} port using D/A converter, and to connect a digital potentiometer, whose resistance can be digitally controlled by a computer, to give it the same resistor value as R_{th} . However, it is not advisable to directly connect a D/A converter to a power consuming real circuit. It is more secure to separate D/A converter and real circuit, and use an OPAMP as a voltage follower (Fig.12).

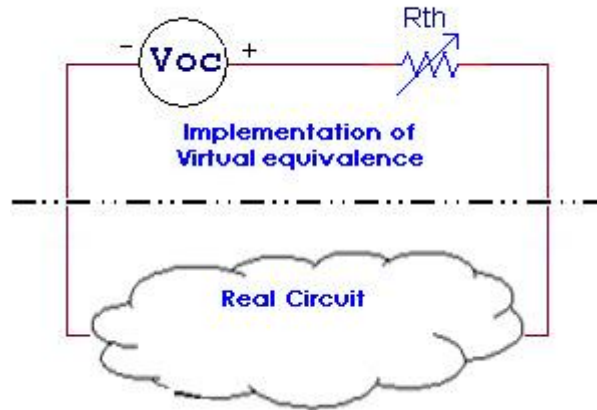


Figure 11. Implementing 2-Port Virtual Equivalence

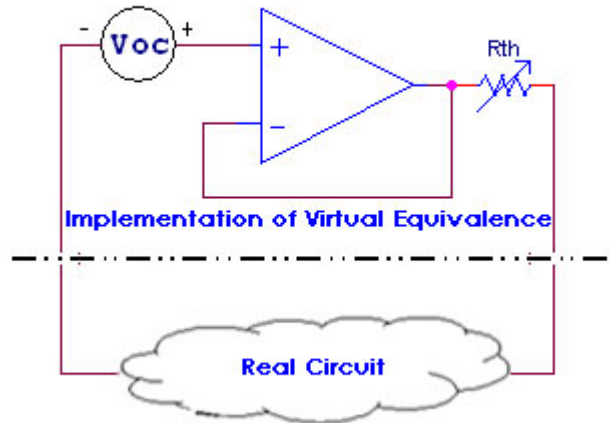


Figure 12. Implementing 2-Port Virtual Equivalence with OPAMP

Fig. 13. is a complete layout for implementing 2-Port Virtual Equivalent Mixed Reality Circuit. DP (R_{th}) is a digital potentiometer controlled by the computer. An A/D converter transmits the signal from the real circuit to the computer, to apply real circuit voltage to the virtual circuit.

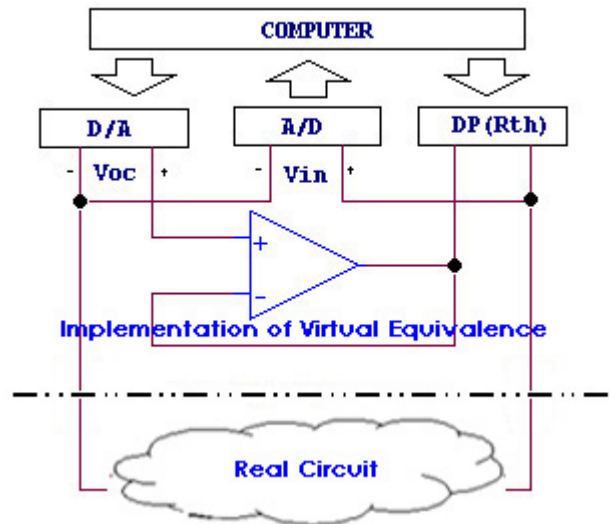


Figure 13. Complete Layout for implementing 2-Port Virtual Equivalence

5. Perspectives

Mixing real and virtual parts of a system may be very helpful for the design of an overall behavior if we want to include components of which we do not have a complete formal model, but can observe their behavior in a connection. Mixed Reality Electric Circuits can be coupled with other mixed reality models. For example, using various CAD applications, which can virtually design and simulate circuits, are already popular in the electronic field as well as in the machinery and architecture design field. And it is possible to merge CAD application (Fig. 14) and mixed reality models (Fig. 3 and Fig. 4) using the *Virtual Equivalence* method, resulting in a very efficient, convenient and powerful mixed reality model.

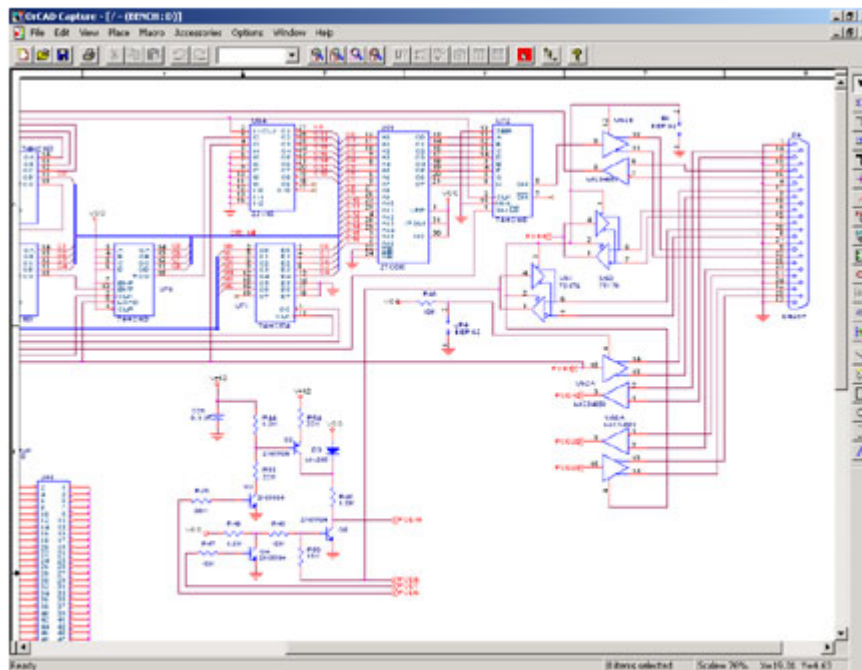


Fig. 14. OrCAD schematic

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